

UNSTEADY SPHERICAL DIFFUSION FLAMES IN MICROGRAVITY

Arvind Atreya, S. Berhan, M. Chernovsky
Department of Mechanical Engineering & Applied Mechanics
University of Michigan; Ann Arbor, MI 48109

and

Kurt R. Sacksteder
NASA Glen Research Center; Cleveland, OH 44135

INTRODUCTION

The absence of buoyancy-induced flows in microgravity (μg) and the resulting increase in the reactant residence time significantly alters the fundamentals of many combustion processes. Substantial differences between normal gravity (ng) and μg flames have been reported in experiments on candle flames [1, 2], flame spread over solids [3, 4], droplet combustion [5,6], and others. These differences are more basic than just in the visible flame shape. Longer residence times and higher concentration of combustion products in the flame zone create a thermochemical environment that changes the flame chemistry and the heat and mass transfer processes. Processes such as flame radiation, that are often ignored in ng , become very important and sometimes even controlling. Furthermore, microgravity conditions considerably enhance flame radiation by: (i) the build-up of combustion products in the high-temperature reaction zone which increases the gas radiation, and (ii) longer residence times make conditions appropriate for substantial amounts of soot to form which is also responsible for radiative heat loss. Thus, it is anticipated that radiative heat loss may eventually extinguish the "weak" (low burning rate per unit flame area) μg diffusion flame. Yet, space shuttle experiments on candle flames show that in an infinite ambient atmosphere, the hemispherical candle flame in μg will burn indefinitely [1]. This may be because of the coupling between the fuel production rate and the flame via the heat-feedback mechanism for candle flames, flames over solids and fuel droplet flames. Thus, to focus only on the gas-phase phenomena leading to radiative extinction, aerodynamically stabilized gaseous diffusion flames are examined. This enables independent control of the fuel flow rate to help identify conditions under which radiative extinction occurs. Also, spherical geometry is chosen for the μg experiments and modeling because: (i) It reduces the complexity by making the problem one-dimensional. (ii) The spherical diffusion flame completely encloses the soot which is formed on the fuel rich side of the reaction zone. This increases the importance of flame radiation because now both soot and gaseous combustion products co-exist inside the high temperature spherical diffusion flame. (iii) For small fuel injection velocities, as is usually the case for a pyrolyzing solid, the diffusion flame in μg around the solid naturally develops spherical symmetry. Thus, spherical diffusion flames are of interest to fires in μg and identifying conditions that lead to radiation-induced extinction is important for spacecraft fire safety.

EXPERIMENTS

The experiments were conducted in the 2.2 sec drop tower at the NASA Lewis Research Center. The drop-rig used is described in detail elsewhere [8]. Briefly, it consists of a cylindrical test chamber (0.38m dia.; 0.43m deep) that houses the spherical burner, the hot-wire igniter and the photodiodes and thermocouples used for making radiation and temperature measurements. The spherical burner (19mm dia.) was constructed from a low heat capacity porous ceramic material (93% porosity). Two

gas cylinders (150 cc & 500 cc) were charged with various gases up to 45 psig and were used to supply the fuel to the porous spherical burner. Fuel flow rates to the burner were controlled by a calibrated needle valve and a gas solenoid valve was used to open and close the gas line to the burner upon computer command. The test chamber also had a 125mm diameter Lexan window which enabled the camera to photograph the flame.

Several μg experiments under ambient pressure and oxygen concentration conditions, were conducted with methane (less sooty), ethylene (sooty), and acetylene (very sooty) fuels for flow rates ranging from 3 to 45 cm³/s. Some experiments with ethylene were repeated with various amounts of CO₂ added to the fuel to increase the radiative heat loss. The following measurements were made and data was collected by an onboard computer during these experiments: (i) *Flame radius* - measured from photographs taken by a color CCD camera. (ii) *Flame radiation* - measured by photodiodes with different spectral characteristics ranging from UV to IR. (iii) *Flame temperature* - measured by five S-type thermocouples and the sphere surface temperature was measured by a K-type thermocouple.

RESULTS

Flame Radius: For all fuels (methane, ethylene and acetylene), initially the flame was blue (non-sooty) but becomes very bright yellow (sooty) under μg conditions. Later, as the flame grew in size it became orange and less luminous and eventually the soot luminosity disappeared. CO₂ diluted flames, however, were mostly blue due to the fuel dilution effect. Both simple analytical and numerical models with one-step chemistry have been developed to explain and understand the expansion rate of these flames. Detailed chemistry models are also being developed. By defining a stream function ' ψ ' to satisfy the mass conservation equation as follows:

$$\frac{\partial \Psi}{\partial t} = -r^2 \rho v; \quad \frac{\partial \Psi}{\partial r} = r^2 \rho; \quad \rightarrow \left(\frac{\partial r}{\partial t} \right)_{\psi} = v$$

The equation for the conserved scalar ' Z ' can be analytically solved with the constant pressure ideal gas assumption and by requiring that $\psi = \text{constant}$ at the flame front. The solution for the flame radius ' r_f ' at time ' t ' is given by the following equation:

$$r_f(t) = \left(R^3 + \left(\frac{3\dot{V}(\rho_o h_{\infty}^s + Q \rho_o Y_{F_{\infty}} Z_c)}{4\pi(\rho_o h_{\infty}^s + \bar{\eta} t)} \right) \times t \right)^{1/3}$$

Where, ' R ' is the sphere radius; \dot{V} is the volumetric fuel flow rate; $\rho_o, h_{\infty}^s, Y_{F_{\infty}}$ and Q are the ambient density, enthalpy, fuel mass fraction and heat released per unit mass of fuel respectively. The flame exists at the conserved scalar value $Z=Z_c$, where ' Z ' is given by the expression:

$$Z = 1 - \operatorname{erf} \left(\frac{\Psi}{2\sqrt{\tau}} \right) / 1 + \operatorname{erf} \left(\frac{M(t)}{8\pi\sqrt{\tau}} \right)$$

Here, $\bar{\eta}$ is the average heat loss rate by radiation per unit volume and $M(t)$ is the fuel mass injected until time ' t '. Note that the effect of heat release, mass flow rate, radiation heat loss rate and diffusion are contained in the factor multiplying ' t ' in the expression for ' r_f '. While these equations

are unlikely to provide comparison with experiments because infinite reaction rates and constant properties are assumed. However, the expression for ' r_f ' may be used to correlate the experimental and numerical results obtained with one-step kinetics. Such a correlation is shown in Figure 1 for several experiments conducted on methane. Similar results were also obtained for other fuels. This correlation shows that the flame radius growth rate is slightly less than $t^{1/3}$.

Flame Temperature:

Figure 2 shows the measured evolution of radial temperature profiles for methane ethylene, acetylene and CO₂ diluted flames. In all cases the fuel flow

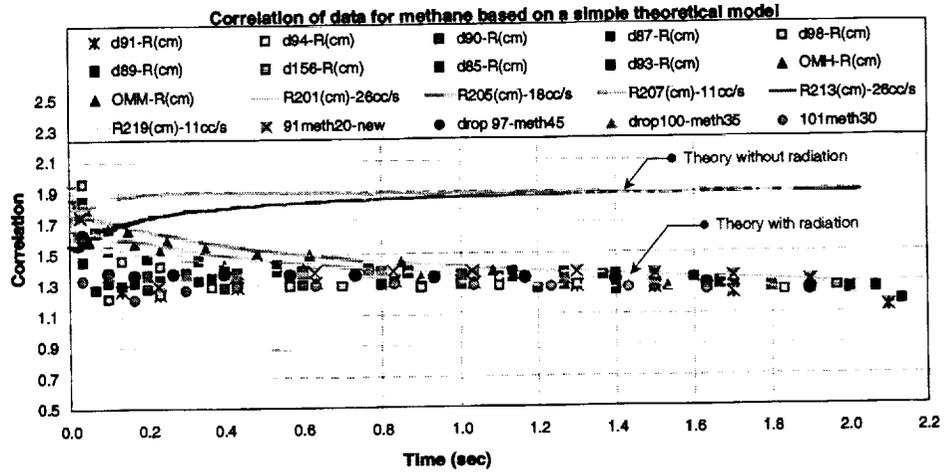


Figure 1: Correlation of data and numerical calculations.

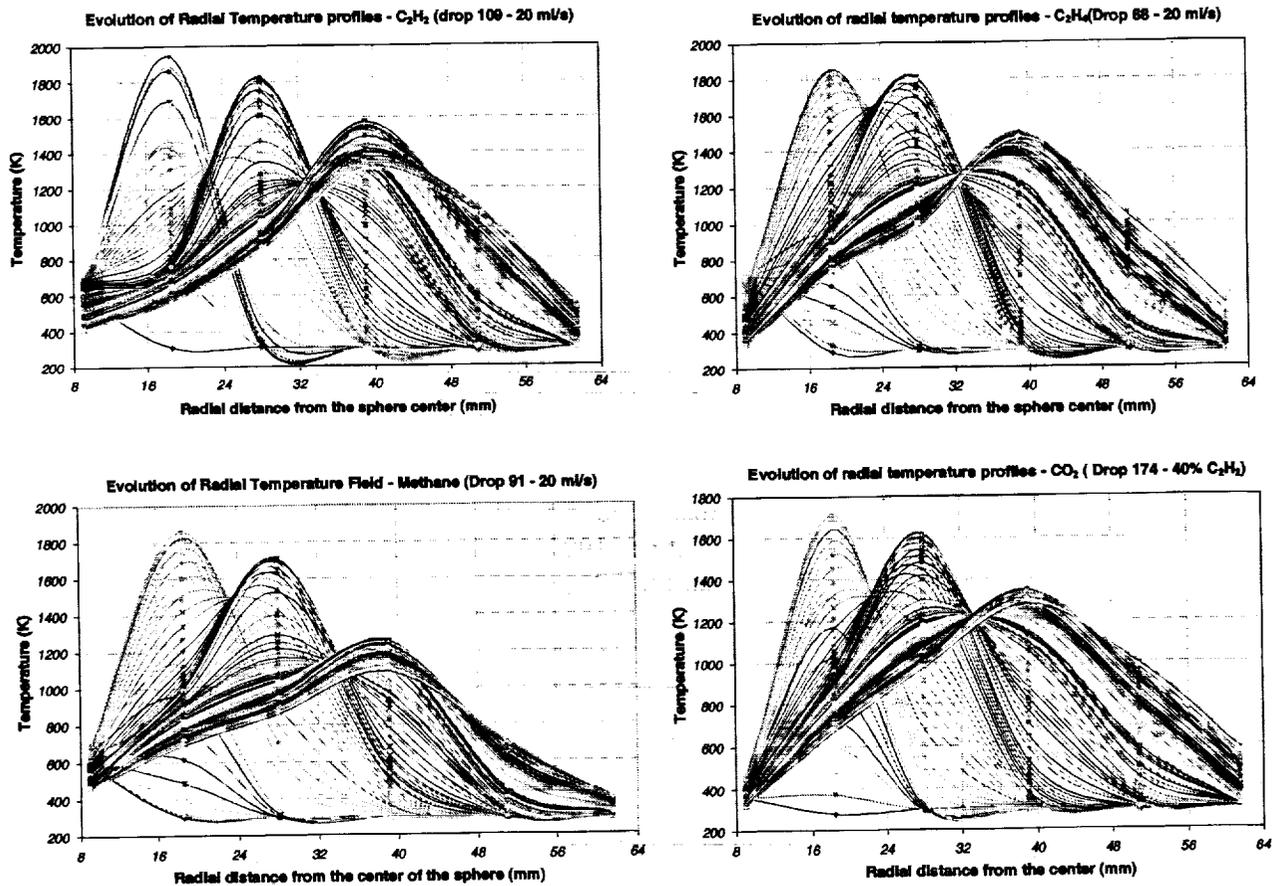


Figure 2: Evolution of radial temperature profiles for four representative cases.

rate was 20 ml/s except for the CO₂ diluted case where the C₂H₄ flow rate was 16 ml/s and the total flow rate was 40 ml/s. Clearly, the temperature fell as time progressed. Also, $T_{C_2H_2} > T_{C_2H_4} > T_{CH_4}$ at all times in the entire domain for the same fuel flow rate. The temperature for $T_{CO_2 + C_2H_4}$ was the lowest. The sooting propensity of these fuels is also in the same order, i.e. $C_2H_2 > C_2H_4 > CH_4$. Thus, we expect that C₂H₂ flames will be the most radiative. It turns out that C₂H₄ + CO₂ flames are the least radiative due to fuel dilution that reduces the temperature. This is shown in Figure 3 below. Only radiation in the CO₂ wavelength for CH₄ & C₂H₄ is shown due to space limitations.

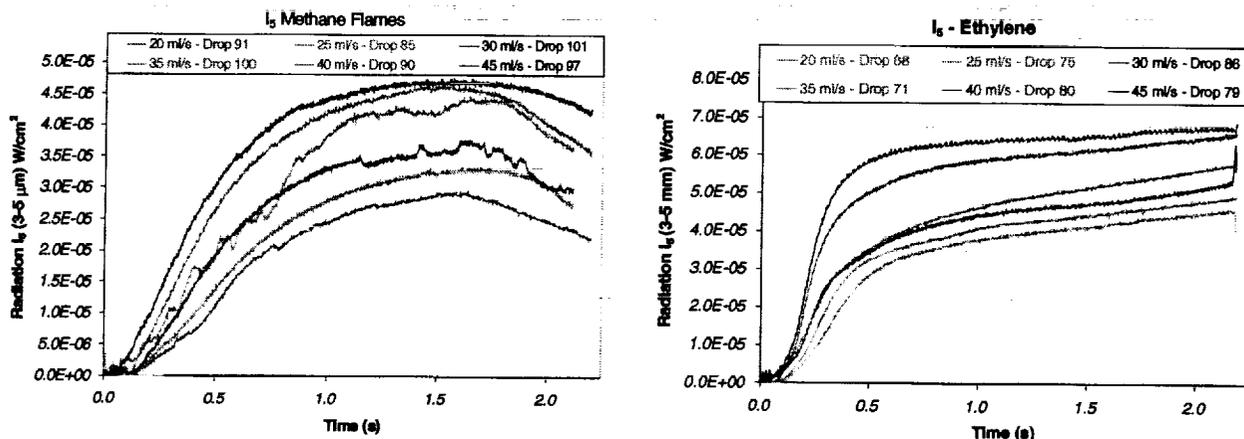


Figure 3: Radiation from CH₄ & C₂H₄ flames in the CO₂ wavelength band.

Figure 3 shows that the flame radiation was reduced roughly by a factor of two for all flames. This is true for all wavelengths as well. Likewise, the radiation from C₂H₂ is higher than C₂H₄ and radiation from CO₂ diluted flames is lower than CH₄ flames for all wavelengths and all flames. This indicates that the effect of temperature is dominant. Interestingly, the total radiation from the pure ethylene flame becomes constant (a trend that is true regardless of the fuel type and the flow rate; in fact for CH₄ it begins to fall) but the total radiation from CO₂ diluted flames continues to increase.

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